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Experimental Studies of Few-nucleon Systems at Intermediate Energies

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Abstract Systems composed of 3 nucleons are a subject of precise experimental studies for many years. At the first stage the investigations were mainly focused on elastic nucleon-deuteron scattering, slowly extending to systematic measurements of the deuteron breakup reaction. Intermediate energies, below the threshold for pion production, deserve special attention: it is the region where comparison with exact theoretical calculations is possible, while the sensitivity to various aspects of interaction, like subtle effects of the dynamics beyond the pairwise nucleon-nucleon force, is significant. Moreover, the Coulomb interaction and relativistic effects show their influence in the observables of the breakup reaction. All these effects vary with energy and appear with different strength in certain observables and phase space regions, what calls for systematic investigations of a possibly rich set of observables determined in a wide range of energies. The next step in complication of the system are studies of reactions involving 4 nucleons—more sensitive, as expected, to subtle dynamics beyond the pairwise interaction. A brief survey of recent and planned experiments in the 3- and 4-nucleon systems is given.

An important, and even basic step on the way to understand properties of nuclei and reactions involving nucleons and nuclei would be to create an exact model of nuclear forces. Even though from the QCD point of view nuclear forces are given as residual interaction between hadrons, successful calculations in the energy region of stable nuclei can be performed with just nuclear and pionic degrees of freedom. At present, there are generally two approaches to the construction of nucleon-nucleon potential: realistic potentials, which are semi-phenomenological models based on meson-exchange picture (see [1] for review), and effective field theories based on spontanously broken chiral symmetry (see [2,3] and references therein). They both provide an accurate description of the very large NN scattering data base below the pion production threshold. The modern potentials were tuned to these large data sets by means of PWA [4,5] and, as a result, the structure of the nuclear force in terms of angular momenta has been established. The nucleon-nucleon potential is undoubtedly a leading part of the nuclear interaction and should be sufficient to describe basic properties of nuclei and main trends in observables for systems of few (and many) nucleons, if only exact calculations are feasible. However, since an internal structure of nucleons is neglected, the question arises, how the suppressed degrees of freedom influence observables in any system consisting of more than 2 nucleons. Such additional dynamics, called

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three-nucleon force (3NF), cannot be reduced to pairwise forces. It arises in the meson exchange picture as an intermediate excitation of a nucleon to a Δ isobar, or it appears fully naturally in ChPT at a certain order. In the first case, there are generally two approaches: 3NF is modelled, like in the case of TM99 [6] or Urbana IX [7] forces, and combined with the given realistic *NN* potential, or the Δ isobar is included explicitly and the coupled channel framework is applied [8,9].

The importance of 3NF contributions for a proper description of systems of more than two nucleons was first established in binding energies of few-nucleon states [10–13]. Studies of 3N systems in nuclear reactions are mainly focused on measurements of observables for elastic nucleon-deuteron scattering and for breakup of deuteron in its collision with a nucleon. Other processes, involving electromagnetic interaction, will not be discussed in this paper. Developments of experimental techniques allowed recently to obtain large data sets representing the precision sufficient for tracing subtle effects, like the mentioned above 3NF. Complete dynamical information on the process can be gained by determining a so-called complete set of observables. Therefore, in addition to differential cross section, the observables related to nuclear polarization are studied, like vector (and tensor) analyzing powers, spin-correlation coefficients or polarization transfer coefficients. The detection system employed depends on the process under study: Magnetic spectrometers with an excellent energy and angular resolution are widely used for studies of elastic scattering. In the case of the breakup reaction, two particles out of three in the final state should be registered for the purpose of resolving kinematic information of the process. Therefore, either a very specific geometry of the outgoing particles is chosen or a detector with a large acceptance is used to cover a big part of the phase space. The latter solution, feasible with modern detection and acquisition systems, has a great advantage that the effects of various dynamical ingredients can be studied in function of a set of kinematic variables.

Extensive discussions of the present status of understanding of the 3*N* system dynamics, based on the modern calculations and many precise and rich data sets, can be found in recent reviews [14–16]. The region of intermediate energies, from roughly 40 MeV/nucleon up to pion production threshold, deserves special attention: It is the region where comparison with exact theoretical calculations is possible and, at its low limit, even ChPT calculations at the currently attainable order can be tested. Moreover, a sensitivity to various aspects of interaction, including 3NF, is observed. The models of 3NF turned out to be an efficient remedy for a long persisting problem of describing cross section for nucleon-deuteron elastic scattering [17–19]. Though at beam energies above 100 MeV per nucleon certain problems with describing the data have been observed (cf. [20] and references therein), improvement of description of the cross section data due to the inclusion of 3NFs is still considerable. However, precise experimental data demonstrate both, success and difficulties of the current models in describing analyzing powers, spin transfer and spin correlation coefficients for elastic scattering [21–31]. This indicates problems with the spin part of the models of the 3*N* interaction. A very wide experimental program has been carried out at KVI to confront these findings against the results of measurements of the breakup reaction: It comprised studies of the ^{1}H(**d**,pp)n and ^{2}H(**p**,pp)n reactions with deuteron beams with energies of 100, 130 and 160 MeV and proton beams with energies of 135 and 190 MeV. The detection systems covering large part of the phase space were employed [16,20,32]. Conclusions on the role of 3NF for the description of the cross section for the breakup reaction are to a large extent similar to the observations for the elastic scattering. The significance of 3NF for a correct description of the differential cross section has been confirmed [33,34]. Moreover, deuteron vector analyzing powers of the breakup reaction at 100 and 130 MeV are equally insensitive to any additional dynamics beyond the pure *NN* interactions as it was observed in the d-p elastic scattering at the same energies [35,36]. On the other hand side, for the tensor analyzing powers of the breakup reaction at the same beam energies, locally certain discrepancies are observed [35], even if (or when) 3NF is included into calculations. The experimental studies of the ^{2}H(**p**,pp)n reaction at 135 and 190 MeV [37,38] show that for vector analyzing power A_y^p a large discrepancy between the measured data and the theoretical predictions can be observed at small relative azimuthal angles of the two breakup protons and this deficiency even increases when including three-nucleon force. The discrepancy rises with energy and the predicted relativistic effects do not explain this behaviour. These facts confirm a problem with the description of spin obsevables in 3N systems. The precise data sets for polarization observables of the ^{1}H(**d**,pp)n at the beam energy of 270 MeV, collected at IUCF [39] and at RIKEN [40], showed also "a mixed picture" in the sector of spin observables. For example, A_y obtained in several angular configurations is described properly by the pure NN force predictions, while including 3NFs leads to a deterioration of the agreement [40]. It has been found that such behaviour is opposite to the one in the elastic scattering at 270 MeV.

In contrast to the elastic scattering, practically insensitive to either Coulomb interaction [41] or relativistic effects [42] over a wide range of energies, the breakup reaction reveals, due to variety of kinematical configurations of its final state, local sensitivity to both of these effects [43–45]. Coulomb effects turned out to be

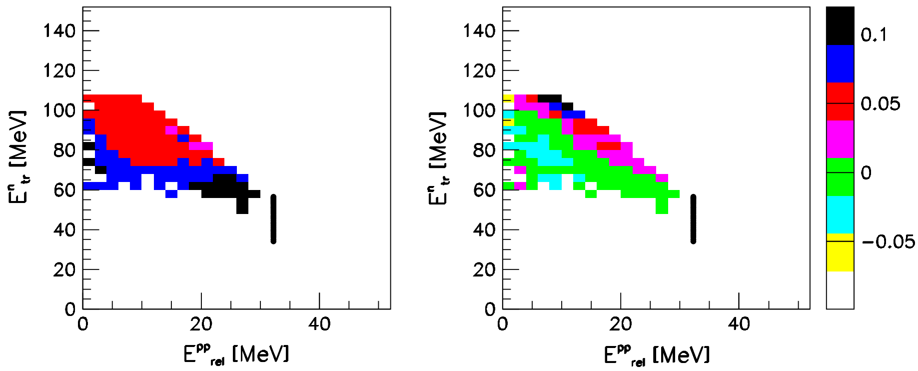

Fig. 1 Net effects of Urbana 3NF (*left*) and of Coulomb force (*right*) in the differential cross section of the *d-p* breakup at 130 MeV, presented as function of two invariant variables. Theoretical predictions obtained by Deltuva et al. with the realistic AV18 potential

surprisingly large [34,46], what motivated the experiment probing the part of phase space particularly sensitive to Coulomb interaction. The measurement was carried out at FZ-Jülich with the use of deuteron beam of 130 MeV and the GeWall detector [47] covering the very forward angles. A strong influence of Coulomb effects and a general success of the theoretical calculations in incorporating this long range interaction was confirmed [48]. In view of interplays of various effects in the breakup reaction, it is of great importance to compare experimental data to calculations including all the dynamical ingredients. A significant progress in this respect has been achieved in recent years, and currently calculations combining 3NF and Coulomb interactions are available [49] as well as relativistic calculations including 3NF [42]. That, in turn, requires systematic experimental studies to test these theoretical predictions on the basis of large and precise data sets.

Following its success in the two-body system, PWA for 3N system could be considered as a valuable source of information on 3NF, but the relevant theoretical framework does not exist so far (see discussion in [15]). Richness of the data base calls, however, for a systematic survey of the results and for comparison of the effects observed in the elastic scattering and the breakup reaction on the same footing. For that purpose, it is clearly advantageous to apply invariant variables. They can be e.g. constructed similarly to Mandelstam invariants and, for convenience, redefined to correspond to the energy of relative motion of two nucleons (pp, pn pairs), E^{pp}_{rel}, E^{pn}_{rel} and the kinetic energy "transferred" to a particle (for definitions and discussion see [16]). Predicted effects of Urbana 3NF and of Coulomb interaction in the differential cross section of the breakup reaction at 130 MeV, presented as a function of two out of four such independent variables, are shown in Fig. 1. The shapes of the distributions correspond to the acceptance of the experiment [34], while colors show changes in the magnitude of the effects. The kinematical points corresponding to the elastic scattering events registered in the same experiment are shown as black dots. Invariant variables for the elastic scattering are not independent, therefore they group on a line. The 3NF effects presented in Fig. 1, left panel, are very local - the strongest in the region kinematically close to the elastic scattering. It is not surprising that the Coulomb effects shown in Fig. 1, right panel, are also local and concentrated near the proton-proton FSI configuration, therefore far from kinematics of the elastic scattering. One can also observe regions where these effects change abruptly from positive to negative due to Coulomb force "pushing out" events from certain kinematical regions to the neighbouring ones. The discussion of theoretical predictions is carried out in the phase space part, where the data points collected in just one experiment exist, what shows outstanding research potential of modern measurements with large acceptance detectors. The analysis of experimental data performed in a function of E^{pp}_{rel} confirms to a large extent the predictions on the size and tendencies of 3NF and Coulomb effects [16].

New data, covering large phase space regions and exploring various observables are needed for systematic investigations of three-nucleon continuum over a wide energy range. The planned measurements with PAX detector at FZ-Jülich would supplement the region of energies below 50 MeV/nucleon with a rich set of data for various spin observables. In the sector of differential cross sections, the experiment using WASA detector and deuteron beam of energies from 170 to 200 MeV/nucleon is currently being performed at FZ-Jülich, while lower (proton) beam energies can be investigated in near future with the BINA detector at the newly opened Cyclotron Center Bronowice (Cracow, Poland).

Even though the investigations of the $3N$ continuum are far from being complete, another step in direction of increasing complexity of the system: studies of reactions with four nucleons, is considered. The $4N$ ensemble reveals already the complexity of heavier systems, e.g. variety of entrance and exit channels, various total isospin states etc. This poses challenges, but also introduces an enhanced sensitivity to certain aspects of the nuclear dynamics, manifested in various channels and configurations. A simple combinatorial consideration that the number of three-nucleon configurations in the four-nucleon system is larger than in the $3N$ system, leads to the conjecture on increased sensitivity to the effects of 3NF. Expecting next milestone in theory - the ab-initio calculations for 4-nucleon systems at intermediate energies - experimental studies of such systems are carried out. The data base at intermediate energies is gradually created in the domain of elastic scattering at deuteron energies of 241 MeV [50] and 135 MeV [51] and the breakup reaction at 135 MeV [52] and 160 MeV. So far, the comparison of quasi-free scattering in the *d(d,pd)n* breakup (with neutron as a spectator) with the elastic *dp* scattering can be performed [52], while rich data sets are collected as the testing ground for future calculations.

Due to recent progress in experimental techniques, the database for the 3- and 4-nucleon system studies at intermediate energies has been significantly enriched. Continuum of breakup states is studied in experiments employing detection systems covering large parts of the phase space, what makes feasible the analysis of observables as a function of kinematical variables. For a sake of comparing data obtained at different energies, the analyses should rely on invariant variables, rather than on the classical ones, related to geometrical configurations. New data sets will be collected in the near future for such systems, complementing the basis for tests of the state-of-the-art and forthcoming theoretical calculations, helping to understand details of the few-nucleon system dynamics.

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